

AD-A241 511

PAGE

Form Approved
GSA No. 3704-0188Public report
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1. AG4P

91 APR 30

2. REPORT TYPE AND DATES COVERED

Interim 90 APR 1 - 91 MAR 30

3. TITLE AND SUBTITLE

NEURO-TRIGGERED TRAINING

5. FUNDING NUMBERS

F49620-90-C-0026

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AFOSR-TR- 91

8. PERFORMING ORGANIZATION
REPORT NUMBER

0784

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

USAF, AFSC
Air Force Office of Scientific Research
Bldg 410
Bollin, AFB DC 20332-644810. SPONSORING/MONITORING
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unlimited

This document has been approved
for public release and sale; its
distribution is unlimited.

12b. DISTRIBUTION CODE

DTIC
ELECTE
OCT 10 1991
S D D

13. ABSTRACT (Maximum 200 words)

Abstract

In the past year we have made good progress in two areas: 1) software for the Neuro-Triggered Training (TRIGGER) system has been designed and is currently being implemented; and 2) analysis of data from a pilot study of working memory has been completed, graphics produced, and a paper written for submittal for publication.

*Original contains color
plates: All DTIC reproduct-
ions will be in black and
white*

91-13040



14. SUBJECT TERMS

Working Memory, Cognition, Feedback, Learning

15. NUMBER OF PAGES

13

16. PRICE CODE

17. SECURITY CLASSIFICATION
OF REPORT

Unclassified

18. SECURITY CLASSIFICATION
OF THIS PAGE

Unclassified

19. SECURITY CLASSIFICATION
OF ABSTRACT

Unclassified

20. LIMITATION OF ABSTRACT

Unlimited

270 0101 10

NEURO TRIGGERED TRAINING

AFOSR Contract F49620-90-C-0026

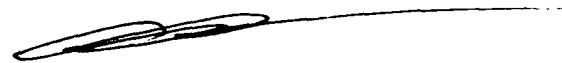
INTERIM TECHNICAL REPORT
1 APR 90 to 31 MAR 91

Approved For	
NTIS	CR-90
DDIC	198
Unpublished	
Justification	
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Distribution	
Date	
Dist	Avail
A-1	

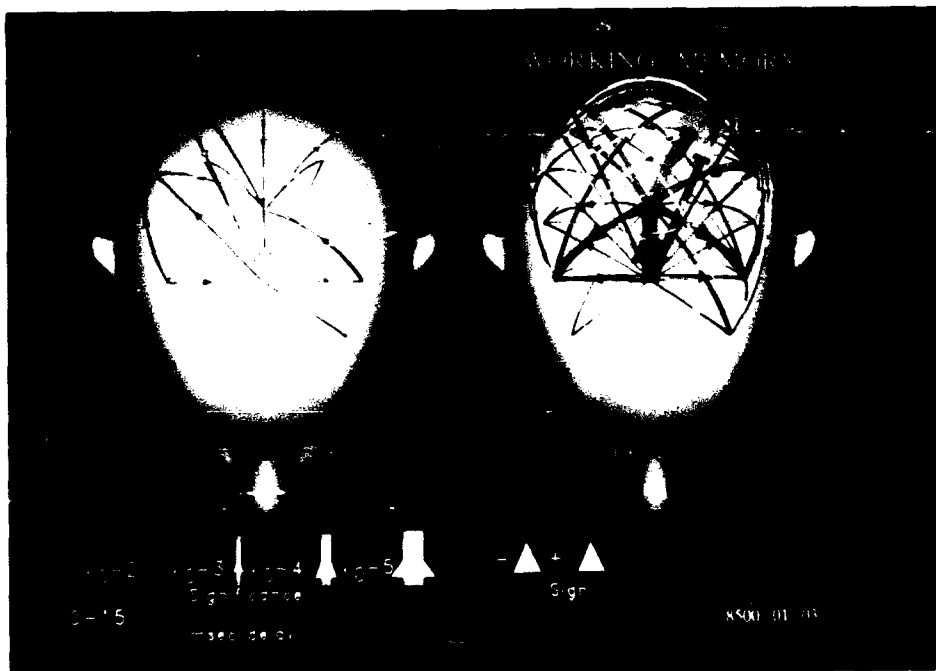
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The views and conclusions in this document are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the Air Force Office of Scientific Research or the U.S. Government.

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PUBLICATIONS AND PRESENTATIONS

Gevins, A.S. and Illes, J. (1991) Neurocognitive networks of the human brain. In: Zappulla, R.A. (Ed.) *Windows on the Brain: Neuropsychology's Technological Frontiers*. New York Academy of Sciences: New York.

Gevins, A.S., Brickett, P., Costales, B., Le, J., Reutter, B. (1990) Beyond topographic mapping: Towards functional-anatomical imaging with 124-channel EEGs and 3-D MRIs, *Brain Topography*, 3(1), pp. 53-64.

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Gevins, A.S., Bressler, S.L., Cutillo, B.A., Illes, J. and Fowler-White, R.M., Miller, J., Stern, J., Jex, H. (1990) Effects of prolonged mental work on functional brain topography. *EEG clin. Neurophysiol.*, 76, pp. 339-350.

Gevins, A.S. (1990) Analysis of multiple lead data. In: J. Rohrbaugh, R. Johnson, R. Parasuraman (Eds.), *Event-Related Potentials of the Brain*. Oxford University Press: New York, pp. 44-56.

Poster Presentation: Cutillo, B., Bressler, S. and Gevins, A. (1990) Spatiotemporal Dynamics of Human Working Memory. *Society for Neuroscience 20th Annual Meeting, St. Louis, Missouri*.

President's Invited Lecture: A. Gevins (1990) *Society for Neuroscience 20th Annual Meeting, St. Louis, Missouri*.

Special Lecture: A. Gevins (1990) *First International Congress on Brain Electromagnetic Topography, Osaka, Japan*.

NEURO-TRIGGERED TRAINING (TRIGGER).

The objective of the Trigger project is to determine the feasibility of a method to accelerate the learning of a task, and optimize its performance by delivering stimuli at instants when preparatory attentional networks are optimal. We plan to achieve this objective by determining the prestimulus EEG patterns associated with a subject's accurate task performance using neural-network pattern recognition, and then training the subject to produce those patterns on a single-trial basis.

We have formulated a detailed plan for executing the project and are currently in the process of programming the Trigger system. Brian Cutillo, the Co-PI, is managing the day-to-day conduct of the project. The programming is being supervised by Jim Johnston, a physicist who is experienced in both PC programming and EEG feedback systems.

A 486 PC has been purchased, and we are adapting existing software to record EEG and behavioral

information. We are redesigning the stimulus presentation and data analysis/display software in a way that will allow easy modification of the Trigger system in the course of future development. For efficiency, a menu system has been written which is used to set and adjust task and feedback parameters during system development and which will be used later when training subjects. The first task we are implementing is our Bimanual Visuomotor Task (Gevins et al., 1989a), but the modular program design will allow other tasks to be conveniently added.

The project plan is to:

1. Program the PC to present the Bimanual Visuomotor Task with behavioral feedback and end-of-block behavioral summaries while collecting EEG, EOG and EMG data.
2. Record 10 channels of EEG, right and left hand EMG, 2 channels of EOG, and the output of 2 finger pressure transducers from a subject performing the Bimanual Visuomotor Task.
3. Quantify behavioral variables including response time, pressure, duration, accuracy and the adaptive error tolerance (as a measure of ongoing performance level). Use the behavioral variables to form data sets of accurate and inaccurate task trials, statistically balanced for confounding variables (especially response variables).
5. Decide what features to use in classifying the accurate and inaccurate trials using the SAM neural network pattern recognition program.
6. Program the PC to extract these features on-line.
7. Implement an on-line algorithm to detect lateral and vertical eye movements and blinks, and incorrect finger movements or hand EMG activity, and abort the trial if such activity occurs.
8. Run the Trigger system in full neurotrigger mode.

When these goals are achieved, hopefully by the end of year 2, we will begin pilot recordings to fine tune the system prior to a formal experiment.

PILOT STUDY OF WORKING MEMORY.

Data for this study were recorded several years ago under USAFSAM sponsorship, but never previously analyzed.

Working memory is a component operation involved in almost all mental activity. These results may well be the first measurements ever made of the rapidly shifting functional cerebral networks of human working memory. A full report of this study, titled "DYNAMIC NEURAL NETWORKS OF HUMAN WORKING MEMORY" has been completed for submission for publication, and is included here.

DYNAMIC NEURAL NETWORKS OF HUMAN WORKING MEMORY

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Cortical neuroelectric patterns during a working memory task differed from a control task during two of four split-second intervals when access to the contents of working memory is assumed to take place. Prefrontal cortical areas were prominent among those differentially activated by working memory in these two intervals, which included a prestimulus preparatory interval and a late poststimulus response-inhibition interval. By contrast, patterns were similar between conditions during an early poststimulus interval and during a response interval, when the predominant activity was related to stimulus encoding or response execution. These results suggest that working memory is a dynamic process embodied in neuroelectric activity patterns distributed across the neural areas involved in performing a particular task.

The active aspect of short-term memory, termed "working memory" by A. Baddeley and co-workers (1), provides the basis for consciously directed perception, cognition and action, attentional programs, and extended logical and linguistic operations. In Baddeley's view, working memory is a limited capacity, unitary process that operates in tasks involving different sensory modalities and types of information by means of just two subprocesses: an "articulatory loop" and a "visuospatial scratchpad", under "executive" control of frontal cortex (2). Other researchers, however, have argued for a more sophisticated view of working memory as an interacting network of relatively independent subsystems which change with the nature of the task (3). From a neurophysiological viewpoint, since working memory can involve different sensory modalities, motor programs and types of information, it is likely that a different constellation of neural subsystems is invoked for each particular type of task. Further, it appears that the prefrontal cortex is critically involved in setting up these constellations of subsystems, and possibly also in maintaining the mnemonic codes themselves (4). These issues have been unresolved because of the lack of direct measurements of the neural substrate of human working memory. Here we report the first measurements of dynamic activity patterns of cortical networks associated with a working memory task in humans. Rather than viewing working memory as a buffer that is filled and emptied, our results suggest that working memory is a function of distributed neural systems by which various types of sensory, motor and higher-order information are maintained for brief periods of time until utilized in a cognitive operation or behavior.

An experimental paradigm was designed in which stimuli, finger movements, and eye movements were equivalent for both control and experimental conditions, but where working memory was utilized only in the experimental condition. Thus a strong inference could be made that differences in neuroelectric patterns in the experimental condition would be due only to type of memory process (i.e., working memory). The control task involved the use of procedural motor memory to produce pressures with the right index finger proportional to visual stimulus numbers from 1 to 9 (5). The

working memory (WM) condition required the same type of finger pressure response, but response magnitude was proportional to the stimulus number seen two trials (about 12 seconds) previously. In order to prevent response initiation before the current stimulus number was processed, no response was required in a random 20% of trials (called targets) when the current stimulus number was the same as the two-trials-back number in the WM condition, and when the number "0" was presented in the control condition (Figure 1). Each trial began with the disappearance of an "X" from the center of the screen and the appearance of a fixation point, which remained on the screen throughout the trial, followed 750 msec later by the stimulus number. Subjects responded with a pressure proportional to the number on a linear scale from 1 to 9. A two-digit feedback number indicating the exact force applied was presented one second after peak response pressure. In addition to providing the subject with information needed to calibrate his responses, this numeric feedback increased task difficulty in the WM condition by causing interference with the numbers being remembered. Each trial lasted about 6 seconds. Control and WM conditions were presented in randomized blocks of 200 trials each.

During an initial training session, 5 right-handed, adult male subjects practiced each condition until reaction times and accuracy reached asymptotic levels. On the next day, the subjects performed 400 trials of each condition while their EEG was recorded from 27 scalp electrodes, along with eye-movements and right-hand *flexor digitorum* muscle activity (EMG) (6). The data were visually edited to remove artifacts, and trials with inappropriate index finger muscle activity (e.g. tensing prior to the response, prolonged tensing after response, or muscle tension on no-response trials) were also deleted. Data sets for the WM and Control conditions were formed from the remaining trials in which the response accuracy was equal to or above the mean accuracy. The data sets were then balanced between Control and WM conditions by deleting outlier trials based on response variables including magnitude, duration, and velocity. The final data sets were thus composed of trials which did not differ ($p > .2$) between WM and Control in terms of stimulus, response or performance accuracy factors, and differed only in the use of working memory.

Averaged evoked potentials (EPs) were computed and examined to identify the amplitude and latencies of the major peaks and waves for each subject for each condition. The EPs were then spatially sharpened using a least-squares estimate of the Laplacian operator to reduce blurring of the potentials due to volume conduction through the skull and other tissues (7). The resulting EPs were then averaged across subjects, and lowpass or bandpass filters were applied to the "grand average" EPs to isolate and enhance individual peaks and waves (see below) (8). Event-Related Covariances (ERCs) were then computed between all pairwise combinations of the 18 non-edge recording positions to characterize rapidly shifting, task-related cortical network activity patterns (9). This measure is based on the observation that when two areas of the brain are functionally related, there is a consistent statistical relationship between their macropotentials in terms of waveshape, amplitude and lag time (10). ERCs were computed as the maximum covariance, and the lag time at which the maximum covariance occurred, between segments of the filtered grand average EPs recorded from different sites. Lag times were ± 64 msec for the 188 msec wide intervals, and ± 96 msec

for the 375 msec wide intervals (see below). Their significance level was determined by statistically comparing each ERC magnitude with a distribution of "non-event-related" covariances computed from the same data but with data segments randomly selected in time within the trials. ERCs were computed in each of four successive split-second intervals whose location was determined from an EP peak or wave: 1) Awaiting Stimulus (Contingent Negative Variation), 2) Stimulus Processing (P100-N100 peaks), 3) Response Inhibition/Target Detection (P300 in no-response trials), and 4) Response Execution (Movement Potential). Similarity of ERC patterns between the two conditions was measured with the Pearson correlation coefficient (Table 1 -- Pattern Similarity). Comparison of the sites with the largest overall covariance was assessed with the Spearman correlation coefficient computed on the ranks of the sums of significant covariance of each site with other sites (Table 1 -- "Hotspot Similarity").

Awaiting Stimulus: During the 750 msec epoch from disappearance of the X until appearance of the stimulus number, preparatory processes related to stimulus encoding and response execution were expected to take place in both conditions. Processes during the preparatory interval of the WM condition were expected to be more complex for two reasons: the motor preparation was expected to be specific because the required response pressure was known prior to onset of the stimulus, and in addition, the one-back stimulus number was being maintained by working memory. The prestimulus evoked potential wave (Contingent Negative Variation) was significantly larger in the WM condition (Student's t -test: $p < .05$). After lowpass filtering with a corner frequency of 7 Hz, ERCs were computed across an interval extending from 500 to 125 msec before the stimulus. The ERC pattern for WM had a relatively low correlation with the Control pattern (0.37 by Pearson correlation, $N=78$), as did the similarity of ERC "hotspots" (Spearman $r = 0.37$). The ERC pattern for the WM condition was more widely distributed, and involved more left hemisphere sites, than the Control condition (Figure 2). Left hemisphere antero-occipital, parietal, antero-parietal and frontal sites were involved in WM but not in Control. Since it was necessary to remember two numbers during the prestimulus interval of the WM condition, the relative left-sidedness of the ERC patterns may reflect the maintenance of active verbal codings in working memory. The covariance between midline antero-central and central electrodes was common to both conditions, as were bilateral antero-central, and right hemisphere antero-parietal and antero-occipital covariances. Since the central and antero-central electrodes overlay premotor and supplementary motor cortices, this pattern may reflect a general preparatory motor set common to both conditions.

Stimulus Processing: The N133 evoked potential peak was maximal at the left midtemporal electrode, where it was larger in WM than in Control ($p < .05$). ERCs were computed across an interval extending from 39 to 227 msec post-stimulus (centered on the N133 peak) after applying a 4-7 Hz bandpass filter to remove the low frequency pre-response potential. ERC patterns for both WM and Control conditions were highly correlated (Pearson correlation = 0.76, $N=105$), and highly similar in rank order of hotspots (Spearman $r = 0.88$). The ERC pattern for both conditions included bilateral antero-occipital, midline and right parietal, midline central and left antero-central sites (Figure 3). These sites respectively overlay visual association, parietal and motor areas which would be expected to be involved in visually initiated, skilled right-handed

finger movements, suggesting that cortical areas for visual stimulus encoding and evaluation, and response planning and execution are functionally related well in advance of overt response initiation. In addition, covariances from the left antero-central to midline frontal, and from midline frontal to bilateral antero-occipital sites suggest a functional coordination of frontal cortex with the right-hand motor and visual association areas. These patterns are consistent with the role of frontal cortex in modulating the activity of these areas (4).

Response Inhibition/Target Detection: Target detection required different kinds of memory operations in the WM and Control conditions. Working memory targets were presumably maintained as active codings, while targets in the Control condition had to be "retrieved" from a longer-term memory. The N200 evoked potential peak was 30 milliseconds earlier and the P300 peak 130 milliseconds earlier for WM targets. The potential distribution of the P300 peak (referenced to computed linked mastoids) had the typical Pz maximum of the parietal "P3b" in both conditions; neither of the peaks had more frontal potential distribution of the "P3a" peak. ERCs were computed from the averaged LD waveforms lowpass filtered at 7 Hz across intervals centered on the P300 peak latency in each condition. These intervals extended from 203 to 578 msec in WM and from 333 to 708 msec in Control. ERC patterns for WM and Control conditions had a relatively low correlation (Pearson correlation = 0.26, $N=153$), as did the rank order of hotspots (Spearman $r = 0.38$). Working memory ERCs had an anterior, slightly left-lateralized distribution, while procedural memory ERCs were focused more posteriorly (Figure 4). This suggests that the matching process in working memory involved greater activity of prefrontal cortical areas. The earlier latencies of the N200 and P300 EP peaks in the WM condition could indicate that the memory match was recognized more quickly, even though the WM task was more difficult and involved a greater memory load than the single, constant target ("0") of the control condition (11). A possible explanation is that the matching of the active codes maintained by working memory with the current stimulus occurred faster than retrieval of the "0" in the control condition.

Response Execution: The Motor Potential (MP) EP peaks did not differ significantly in amplitude between conditions. The corresponding ERCs were computed across intervals from 26 msec pre-response to 162 msec post-response onset, centered on the peak of the MP of the response-registered evoked potentials (bandpass-filtered with the cutoff frequencies at 4-7 Hz). ERC patterns for WM and Control conditions were highly correlated (Pearson correlation = 0.96, $N=86$), as was the rank order of their hotspots (Spearman $r = 0.91$). The MP ERC pattern (Figure 5) was focused over left and midline antero-central (motor) and left antero-parietal (somatosensory) sites, consistent with initiation of an isometric response with the right index finger. This pattern is similar to those measured in previous experiments during skilled right-hand index finger contractions (12).

The differences in the ERC patterns between conditions, and the "paradoxical" shortening of P300 evoked potential peak latency indicate that two different memory functions, rather than different "memory loads", were invoked by the tasks. In the two types of memory functions involved, the information being remembered was embodied

in rapidly changing, task-specific activity patterns which were distributed among the neural systems specific to the particular task. There was an indication in the pre-stimulus and the target identification intervals supporting the role of frontal cortex in working memory (13), which is not unexpected in view of the fact that prefrontal lesions are known to affect procedural and working memory in a differential manner (14). It is likely that Baddeley's two-subsystem model of working memory is a construct of the paradigms used in psychological research, and that at the level of neural networks, there are as many different types of functional networks for working memory as there are types of tasks. All the various functions of prefrontal cortex, such as temporal ordering, sequencing, polymodal integration, response inhibition and delaying the activity of sensory, motor, and posterior association areas may be considered aspects of working memory. Further, prefrontal cortex may be an "active" node in a functional network only during brief intervals when the schema or code it maintains is being utilized by processes in other neural areas. This idea is supported by the findings in the present study that the patterns of functional interrelationship for stimulus registration and response execution do not differ between conditions, while the posterior frontal areas do distinguish the working memory condition in the pre-stimulus interval, when responses are being prepared from information contained in working memory, and in the target identification interval, when the current stimulus registration is being matched with the code maintained by working memory. In addition, lesion and electrophysiological studies suggest that, with the possible exception of schema for the sequencing of internal processes, the actual codes are not retained in frontal cortex, but rather the frontal cortex directs the maintenance of such information in other areas (15). Future studies will have to be performed in order to observe the networks associated with working memory in tasks employing different sensory modalities and modes of information, such as spatial, verbal and numeric (16).

References and Notes

1. A. Baddeley and G. Hitch, in *Recent Advances in Learning and Motivation*, Vol. 8, G. Bower, Ed., (Academic Press, New York, 1974), pp. 47-90.
2. A. Baddeley, *Working Memory*, (Oxford, London/New York, 1986), pp. 224-253.
3. G. Allport, in *Cognitive Psychology: New Directions*, G. Claxton, Ed. (Rutledge and Kegan Paul, London, 1980), pp. 26-64; P. Barnard, in *Progress in the Psychology of Language*, A. Ellis, Ed. (Lawrence Erlbaum, London, 1985), pp. 197-258.
4. V. Frisk and B. Milner, *Neuropsychologia*, 28:2, 121 (1990).
5. A. Gevins, S. Bressler, B. Cutillo, J. Illes, J. Miller, J. Stern and H. Jex, *Electroenceph. clin. Neurophysiol.*, 76, 339 (1990). Stimuli were presented on a Videographics-II CRT placed 70 cm from the subject, subtended a visual angle under 1.5 degrees, were 325 msec in duration, and had an illumination of 11 cd/sq meter against a background of 0.1 cd/sq meter. Each trial lasted about 6 seconds; thus in the 2-back WM condition each number had to be maintained for about 12 seconds. In each grouping of 3 successive numbers in the WM condition, the numbers were con-

strained so that they were all at least 2 standard deviations in a subject's mean response error from each other. Thus by using only "accurate" trials in this error range, we were able to strongly infer that the correct 2-back number was being remembered.

6. Electrodes were placed according to the expanded 10-20 electrode system, in which additional coronal rows of electrodes are interspersed between the standard rows (Gevins, in E. Basar, Ed., *Dynamics of Sensory and Cognitive Processing of the Brain*, Springer-Verlag, Heidelberg, 1988, pp. 88-102). The 27 EEG electrodes were aF1, aF2, Fz, F3, F4, F7, F8, aCz, aC3, aC4, Cz, C3, C4, aP1, aP2, aP3, aP4, Pz, P3, P4, T3, T4, T5, T6, aO1 and aO2, and Oz. The reference was at the right mastoid (A2), and the left mastoid (A1) was also recorded for off-line computation of a linked-mastoid reference. Vertical and horizontal eye movement (EOG), electrocardiogram (ECG), respiration, and EMG from the right-hand index finger *flexor digitorum* muscle were recorded with bipolar electrodes. Output of the finger pressure transducer was also digitized. EEG channels were recorded with a maximum amplitude of 140 uv peak to peak. The bandpass had a 6 db/oct rolloff below .05 Hz and 24 db/oct rolloff above 50 Hz. Digitization onto magnetic tape was at 128 Hz, from .75 sec before stimulus to 1.25 sec after feedback.

7. B. Hjorth, *Electroenceph. clin. Neurophysiol.*, 39, 526 (1975); P. Nunez, *Electric Fields in the Brain* (Oxford, New York, 1981); A. Gevins, *Brain Topog.*, 2:1, 37 (1989). This operation also removes the effect of the reference electrode site. The nine peripheral electrodes were not analyzed because the Laplacian operator could not be accurately computed at the edges of the recording array. The 18 remaining non-edge electrodes were lateral and midline frontal (F4, F3, Fz), lateral and midline anterior central (aC4, aC3, aCz), lateral and midline central (C4, C3, Cz), lateral anterior parietal (aP1, aP2, aP3 and aP4), lateral and midline parietal (P4, P3, Pz), and lateral anterior occipital (aO2, aO1).

8. Differences between subjects in evoked potentials and ERC patterns are the subject of another paper (A. Gevins and B. Cutillo, In Prep.).

9. A. Gevins, N. Morgan, S. Bressler, B. Cutillo, R. White, J. Illes, D. Greer, J. Doyle, and G. Zeitlin, *Science*, 235, 580 (1987); Gevins and Bressler, in G. Pfurtscheller, *Functional Brain Imaging*, pp 99-116 (Hans Huber Publishers, Bern, 1988); A. Gevins, S. Bressler, N. Morgan, B. Cutillo, R. White, D. Greer and J. Illes, *Electroenceph. clin. Neurophysiol.*, 74:1, 58 (1989a); A. Gevins, B. Cutillo, S. Bressler, N. Morgan, R. White, J. Illes and D. Greer, *Electroenceph. clin. Neurophysiol.*, 74:2, 147 (1989b). There is, in general, no certainty that a scalp recorded signal arises in the immediately underlying region of cortex, even when the effect of the reference electrode has been removed and the potentials have been spatially sharpened. However, the weight of the evidence of the specific ERC patterns in this and previous studies, particularly in the case of well understood processes such as stimulus processing and movement execution, is consistent with such an interpretation. Further, the many occurrences of long time lags in covariances between adjacent recording sites, or of strong covariances between two sites with no significant covariances with interven-

ing sites, implies that the patterns being measured are not due simply to volume conducted activity from a distant source. Determining the origin of these patterns in the general case is the focus of ongoing work involving neurosurgery patients.

10. M. Livanov, *Spatial Organization of Cerebral Processes* (Wiley, N.Y., 1977); W. Freeman, *Mass Action in the Human Nervous System* (Academic, N.Y., 1975); D. Thatcher & E. Roy John, *Foundations of Neuroscience*, Vol. 1 (Lawrence Erlbaum, New Jersey, 1977); A. Gevins, J. Doyle, B. Cutillo, R. Schaffer, R. Tannehill, J. Ghannam, J. Gilcrease, and C. Yeager, *Science*, 213, 918 (1981); A. Gevins, R. Schaffer, J. Doyle, B. Cutillo, R. Tannehill and S. Bressler, *Science*, 220, 97 (1983).

11. The latency of the P300 evoked potential peak has been reported to lengthen with increasing memory-load in "Sternberg-type" memory scanning paradigms: N. Adam and G. Collins, *Electroenceph. clin. Neurophysiol.*, 44, 147 (1978); J. Ford, W. Roth, R. Mohrs, W. Hopkins and B. Kopell, *Electroenceph. clin. Neurophysiol.*, 47, 450 (1979); R. Chapman, J. McCrary and J. Chapman, *Canadian J. Psychology*, 35, 201-211 (1981); H. Pratt, H. Michalewski, G. Barrett and A. Starr, *Electroenceph. clin. Neurophysiol.*, 72, 407 (1989). The reported P300 peak latencies to positive probes are in the same range as the P300 peak latency for memory targets in the control condition of our study. The unusually short peak latency of the P300 in the difficult working memory condition of our study could be due to the fact that the previous studies using the Sternberg paradigm compared P300 latencies between different memory "loads" (i.e., number of items in working memory), whereas our paradigm contrasted two *different* memory systems: a working memory system and a procedural memory (control) condition.

12. Gevins et al., *ibid.* (1987) and Gevins, et al., *ibid.* (1989a).

13. It has been postulated that prefrontal cortex is directly involved in mediating working memory - D. Ingvar, *J. Human Neurobiology*, 4, 127 (1985); J. Fuster, *The Prefrontal Cortex*, Raven Press, New York (1989). Similarly, depth electrode evoked potential studies have shown that left posterior frontal and temporal areas are more involved during working memory tasks (E. Halgren and M. Smith, *Human Neurobiol.*, 6, 129 (1987).

14. P. Goldman-Rakic, *Handbook of Physiol.*, Vol. 5, Part 1, pp. 373-417 (1987).

15. J. Fuster, *ibid.* (1989).

16. Supported by grants from the Air Force Office of Scientific Research, the National Institute of Neurological Diseases and Strokes, and The National Institute of Mental Health. Thanks to Steve Bressler, Paul Brickett, Judy Illes and Michael Ward for scientific contributions, and to Roseann White and Judy McLaughlin for assistance.

Table 1. Comparison of Event-Related Covariance (ERC) patterns between Working Memory and Control conditions for each of four split-second intervals (rows). Column one measures how similar the patterns are in appearance. Column two measures the similarity of the strongest covarying sites.

ERC Measure Interval	Overall Pattern Similarity (Pearson r)	"Hotspot" Similarity (Spearman r)
Awaiting Stimulus	$r = 0.37$ $N = 78$	$r = 0.37$ $N = 18$
Stimulus Processing	$r = 0.76$ $N = 105$	$r = 0.88$ $N = 18$
Response Inhibition	$r = 0.26$ $N = 153$	$r = 0.38$ $N = 18$
Response Execution	$r = 0.96$ $N = 86$	$r = 0.91$ $N = 18$

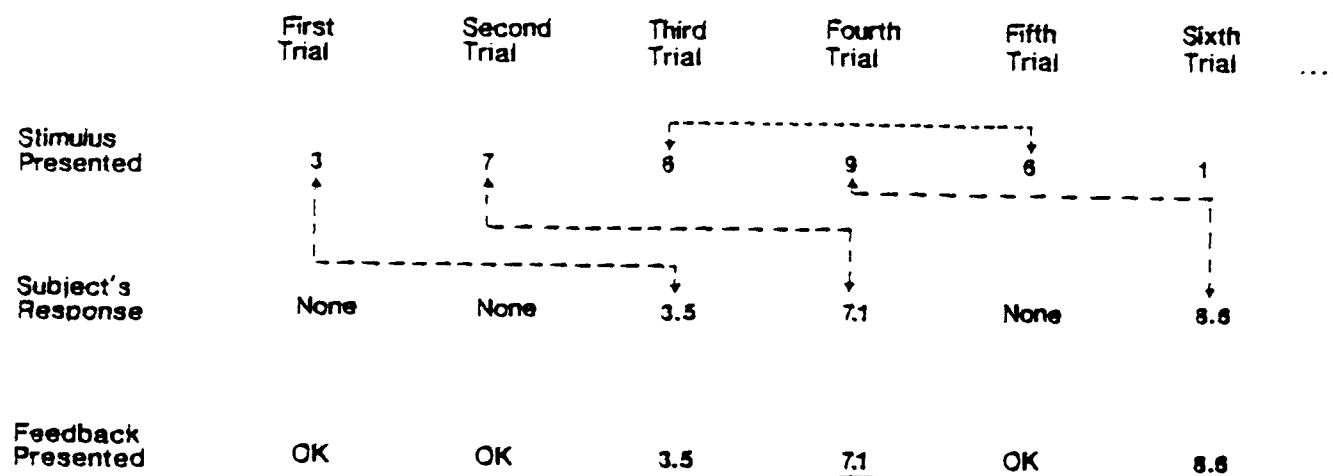


Figure 1. Typical sequence of the first six trials of a block of Working Memory (WM) task trials. On 80% of the trials, subjects responded to the stimulus presented by making a finger pressure whose magnitude was proportional to the stimulus number presented two trials previously. If the stimulus presented was the same as the one two trials back, they were supposed to make no response (random 20% of trials). The feedback presented showed the response they made, and was underlined if the response was accurate.

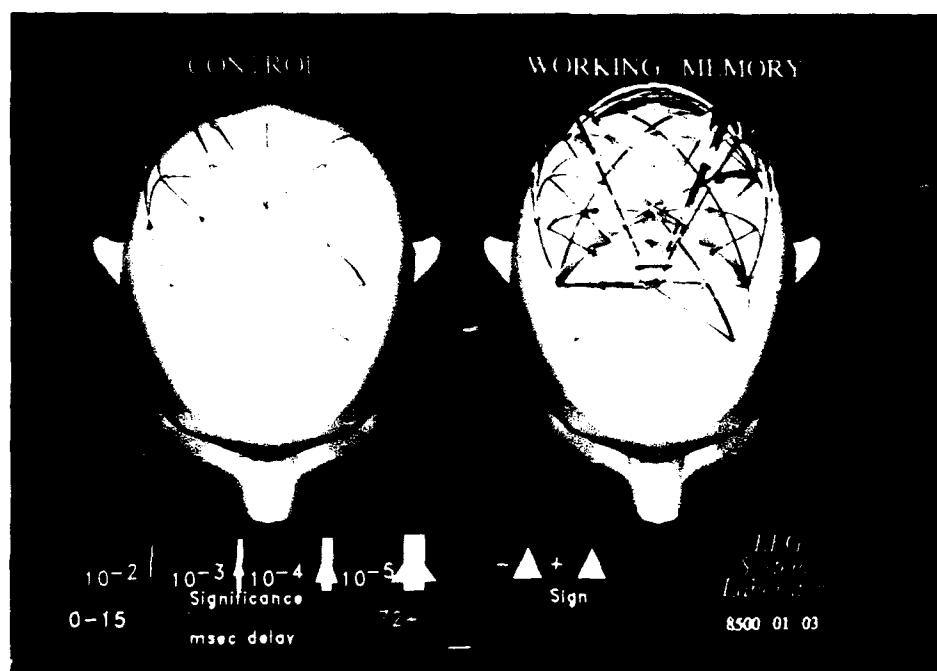


Figure 2. Event-Related Covariance (ERC) patterns during the prestimulus interval of the Control (Left) and Working Memory (Right) conditions recorded from five subjects while they stared at a dot on a computer screen awaiting the next stimulus number. The Working Memory covariance pattern differed from the Control, particularly in covariances involving midline central and antero-central, and left-hemisphere frontal and parietal sites. In all ERC figures, the thickness of a line connecting two sites is proportional to the significance of the covariance of the evoked potential segments recorded from the sites. The color indicates the lag time in milliseconds at which the maximum covariance occurred, and the arrows point from leading to lagging site.

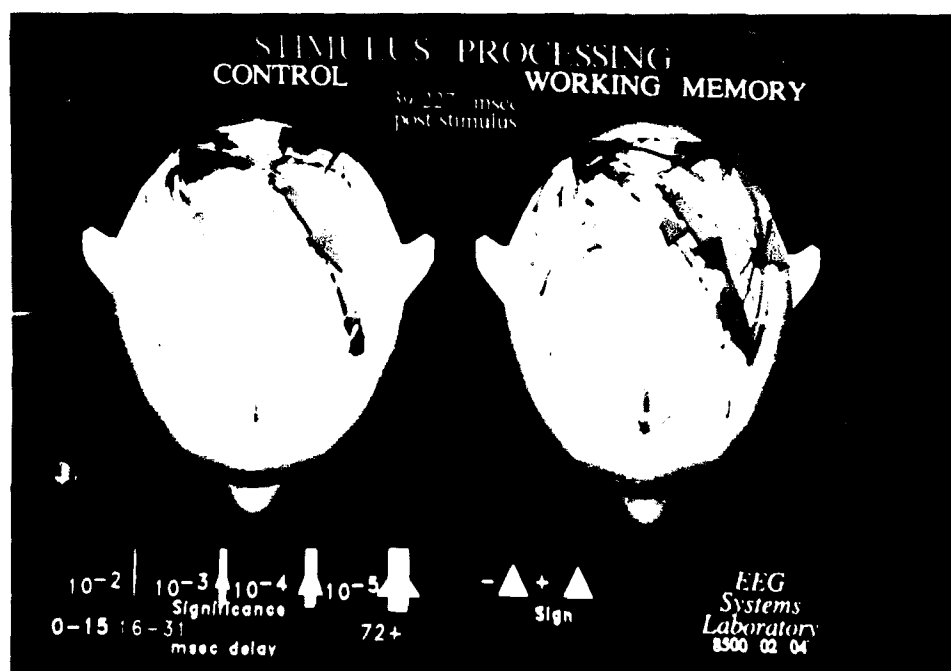


Figure 3. The ERC patterns during the Stimulus Processing interval were very similar in the Working Memory and Control conditions.

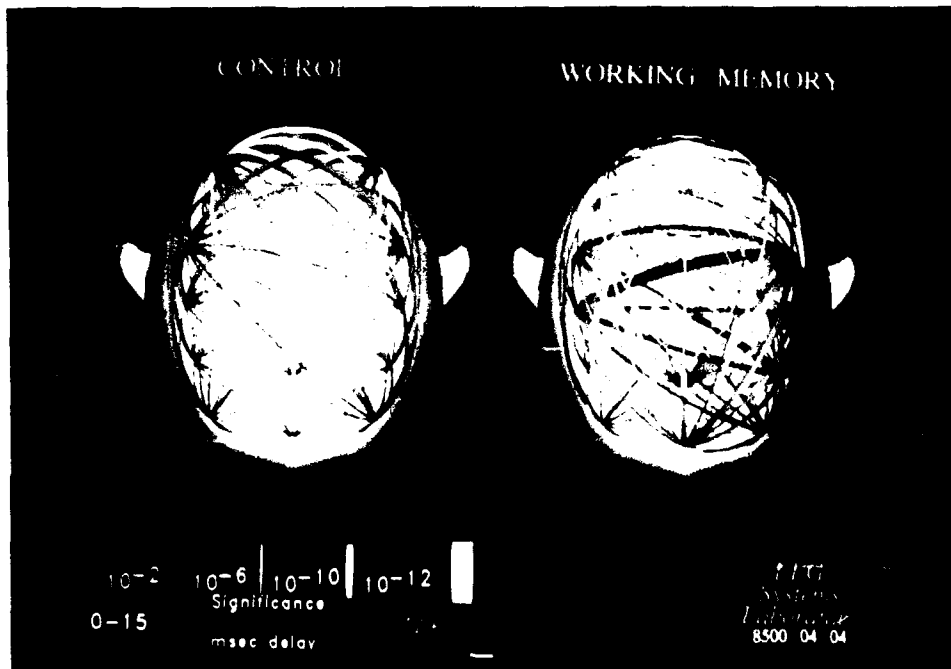


Figure 4. The ERC patterns during the Response Inhibition interval of target trials differed considerable between Working Memory and Control conditions. Working memory ERCs had an anterior, slightly left-lateralized distribution, while control condition ERCs were focused more posteriorly.

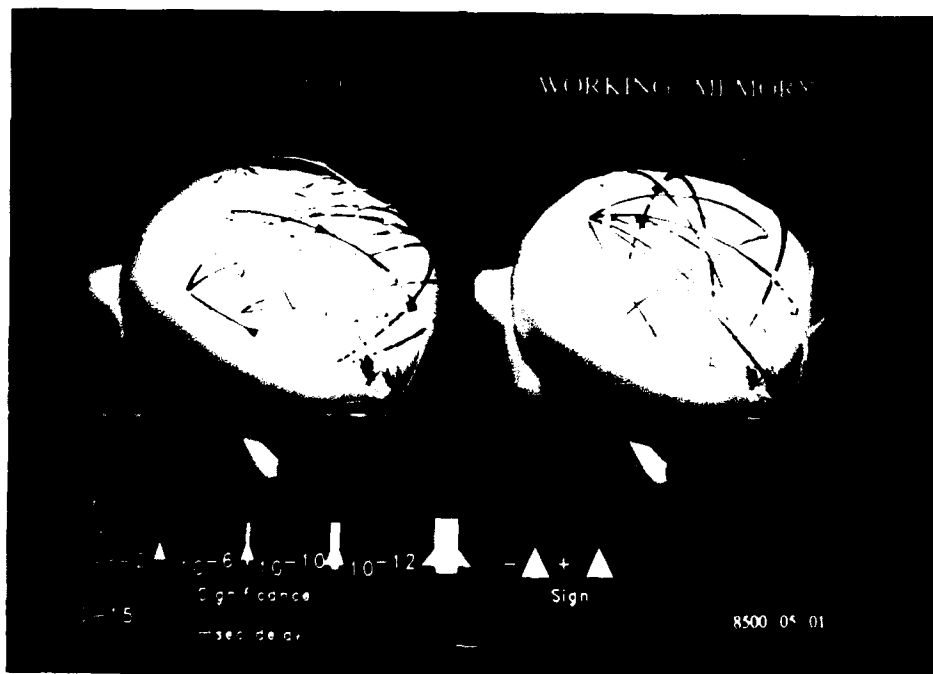


Figure 5. As in the Stimulus Processing interval, ERC patterns in the Response Execution interval were again very similar between Working Memory and Control conditions.